AD-A060 298 UNITED STATES STEEL CORP MONROEVILLE PA RESEARCH LAB F/G 11/6
EFFECT OF PURITY ON RELIABILITY CHARACTERISTICS OF HIGH STRENGT--ETC(U)
JUL 78 S R NOVAK, A W LOGINOW, H M REICHHOLD F33615-75-C-5137
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TABLE F-1 (CONTINUED)

\#\# Calculated relative to the experimentally measured values and equally applicable to both P_f and K_{If} (which differ only by a constant for the same value of a_f) as given by

$$\% \text{ Diff.} = \left[\frac{P_f(\text{theo}) - P_f(\text{exp})}{P_f(\text{exp})}\right] \times 100 = \left[\frac{K_{If}(\text{theo}) - K_{If}(\text{exp})}{K_{If}(\text{exp})}\right] \times 100$$

where the designations "theo" and "exp" refer to the theoretical and experimental values, respectively.

\#\#\# Values of a_f and P_f are associated with either macroscopic crack branching or SCC crack-plane inclination (see Table 9).

\+ N/A = Not applicable due to macroscopic crack branching or SCC crack plane inclination (see Table 9). However, calculations made as if a single (straight) crack plane existed and for the listed values of a_f given above were as follows:

Item No.	Spec. No.	Experimental Values P_f, pounds	Experimental Values K_{If}, ksi√inch	Theoretical Values P_f, pounds	Theoretical Values K_{If}, ksi√inch	Percentage Difference, %
1	44-1	3365	44.4	2489	32.9	-26.0
8	47-1	4645	40.9	8623	75.8	+85.6
9	47-2	7590	65.6	6782	58.6	-10.7

Conversion Factors

1 inch = 2.54 cm = 25.4 mm

1 pound = 4.45 N

1 ksi√inch = 1.099 MPa√m

°C = 5/9(°F - 32)

TABLE F-2

SUMMARY OF EXPERIMENTAL AND THEORETICAL RESULTS AT SCC-TEST TERMINATION FOR TWO 18Ni STEELS*

Item No.	Spec. No.	K_{Io}, ksi√inch	a_o,** inch	a_f,** inches	Experimental Values*** P_f, pounds	Experimental Values*** K_{If}, ksi√inch	Theoretical Values# P_f, pounds	Theoretical Values# K_{If}, ksi√inch	Percentage## Difference, %
				18Ni Normal-Purity Steel					
1	43-1	64.2	0.908	2.257	290	20.0	261	18.0	-10.1
2	43-2	49.8	0.908	1.967	965	22.4	882	20.4	-8.6
3	43-3	39.7	0.924	1.693	1860	24.1	1604	20.7	-13.8
4	43-4	29.9	0.900	1.019	4440	25.7	4524	26.2	+1.9
5	43-5	20.0	0.883	0.961	3345	18.4	3331	18.3	-0.4
6	43-6	10.0	0.927	0.958	1595	8.8	1768	9.7	+10.9
7*	43-7*	64.8	0.902	0.904	12,180	63.8	12,352	64.7	+1.4
				18Ni High-Purity Steel					
8	46-1	99.7	0.897	2.081	1045	33.1	1138	36.1	+8.9
9	46-3	84.8	0.906	1.748	3190	43.0	3134	42.2	-1.8
10	46-2	69.4	0.910	1.811	2310	35.4	2174	33.4	-5.9
11	46-4	59.9	0.901	1.606	3595	37.5	3050	31.8	-15.2
12	46-5	49.9	0.910	1.296	4855	33.7	4764	33.1	-1.9
13	46-6	39.9	0.916	1.191	5730	35.9	4701	29.5	-18.0
14	46-7	30.1	0.902	1.078	3695	21.0	4356	24.7	+17.9

* All results are for 1T modified WOL specimens subjected to bolt-loading and exposed to a 3.5% NaCl solution at +72°F under total immersion conditions for $t_f \cong 7000$ hours (see Table 10)—except for item No. 7, which was subjected to laboratory air at +72°F for $t_f \cong 5700$ hours.

** a_o and a_f are each the average of surface measurements.

*** Based on P_f values measured in a tension-testing machine with the use of a calibrated clip gage under conditions of high sensitivity (see Table E-2).

\# Based on P_f values calculated using the "rigid-bolt analysis" (suitably corrected) as

$$P_f = \left(\frac{a_o}{a_f}\right)\left(\frac{a_f + C_1}{a_o + C_1}\right)\left[\frac{C_6(a_o/W)}{C_6(a_f/W)}\right] \cdot P_o,$$ where P_o is the experimentally-measured original load and $C_1 = 0.60$ inch (1.5 cm).

\#\# Calculated relative to the experimentally measured values as shown in Table F-1.

Conversion Factors

1 inch = 2.54 cm = 25.4 mm
1 pound = 4.45 N
1 ksi√inch = 1.099 MPa√m
°C = 5/9(°F - 32)

this range, whereby the experimental values are generally somewhat higher than those from the rigid-bolt analysis and in the same direction as the higher theoretical values that would otherwise be calculated with the more precise but also more complex relationship of the elastic-bolt analysis. Furthermore, the result for the 25th or excepted specimen (No. 44-2, Table F-1) that was considerably outside the cited agreement range would appear to be somewhat suspect. That is, because macroscopic crack branching was observed for a mating 10Ni normal-purity steel specimen at the next higher K_{Io} level, the result for this excepted specimen may reflect internal crack branching that was otherwise not evident from measurements of crack length made only at the specimen surface.

These results showing agreement within ±18 percent between theoretical and experimental values at test termination (P_f and K_{If}) for 24 of the 25 specimens are possibly even better than should otherwise be expected—at least for a certain group of specimens that exhibited behavior corresponding to large SCC crack extension (Δa_{SCC}) and similar large load reductions from P_o to P_f. That is, a difference between theoretical and experimental values of P_f, in particular, should be put into proper perspective by consideration relative to the total load reduction from P_o. For example, specimen No. 43-1 in Table F-2 yielded theoretical and experimental final load values of P_f = 261 and 290 pounds (1160 and 1290 N), respectively, representing a difference of 10.1 percent. However, when considered relative to the fact that these P_f values represent a load reduction by a factor of 42 to 1 from P_o = 12,210 pounds (54,300 N), the actual difference between these theoretical and experimental values (29 pounds) is indeed quite small and represents only a small fraction (0.25%) of the P_o value. Another example can be seen from specimen No. 46-1 in Table F-2, which exhibited a difference between theoretical and experimental P_f values of only 8.9 percent even though the load reduction from P_o to P_f was a factor of 20 to 1. Similar differences of generally less than 10 percent between theoretical and experimental values of P_f can also be seen for other specimens (No. 43-2, No. 43-3, No. 46-2, and No. 46-3 in Table F-2) that exhibited load reductions from P_o to P_f in the range between 10 to 1 and 4 to 1.

The relatively good agreement between the experimental and approximate theoretical results of the present study in Tables F-1 and F-2 is of major importance in demonstrating consistency for SCC studies conducted using the 1T modified WOL specimen under bolt-loading conditions—both in the present investigation and in other studies conducted generally. In particular, the present results provide strong evidence to demonstrate the absence of any significant or first-order external influences such as wedging action of corrosion products. Concern for such an effect, in particular, has been expressed in other quarters and can be given some merit in view of the relatively long test durations imposed currently ($t_f \geqq$ 7000 hours) and during which the potential for significant corrosion exists. Indeed, it is recognized that such wedging action of corrosion products can occur for cracks contained in steel bodies subjected to SCC conditions. Likewise, it is also known that such effects can occur to very significant degrees for notched and/or cracked aluminum bodies even in the absence of externally applied stress. For SCC tests conducted on aluminum alloys with 1T modified WOL specimens, such effects could presumably lead to complete relaxation of the bolt-applied load that would otherwise be expected to occur for crack extension occurring in the absence of corrosion products. Although the more precise (elastic-bolt) analyses was not used for the theoretical values, the results of the present tests still provide verification that concern for wedging action of corrosion products in the current investigation is not justified or, more specifically, that such influence was either relatively minimal or nonexistent. Furthermore, the present results would seem to indicate the likelihood that similar findings would occur for like investigations of SCC behavior of other steels when tested with the 1T modified WOL specimen under bolt-loading conditions.

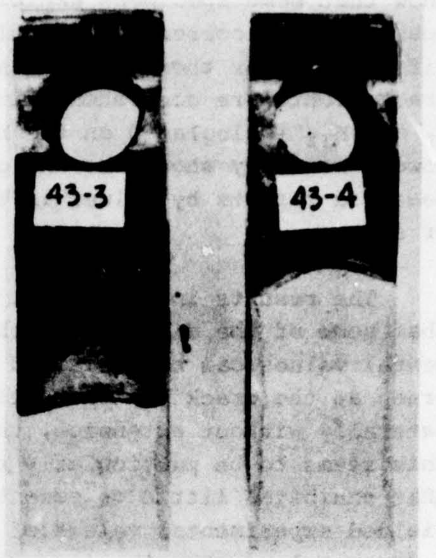
It would appear that total differences between theoretical and experimental values of P_f in the range ±18 percent or less within the current tests can be explained on the basis of a single effect or the combined action of several effects. Four possible effects, each having the potential to account for differences as high as ±5 to ±10 percent in the present study, are discussed in more detail below. No real attempt has been made to quantitatively evaluate the specific contribution of each effect. However, it is important that each be listed and described in general terms to be recognized as a tenable source of difference between theoretical and experimental values of P_f.

The theoretical values of P_f and K_{If} contained in Tables F-1 and F-2 were calculated on the basis of the average of two surface measurements of final crack length made for each specimen at test termination (a_f). One second- or third-order source of difference observed between the experimental and theoretical values of P_f and K_{If} could be that such surface measurements of a_f do not reflect the true average of measurements made through the specimen thickness, B. The theoretical values of P_f and K_{If} could be either higher or lower depending on whether the SCC crack front through the specimen thickness was either primarily convex or concave. Some typical fracture surfaces of specimens in the present study are presented in Figure F-1 and show that the final SCC crack fronts were somewhat irregular, as would be expected, but reasonably straight for most specimens as measured through the specimen thickness (from surface to surface between the values used for the average value of a_f). In addition, the final surface measurements (a_{fR} and a_{fL}) for a particular specimen were always within ±90 mils (±0.090 inch) of the corresponding average a_f value and were within ±30 mils (±0.030 inch) of the corresponding average a_f value for most specimens in the study (21 of 28). Such considerations indicate that differences in calculated P_f or K_{If} values on the order of ±5 to ±10 percent might be estimated crudely to occur as a consequence of the surface a_f values not reflecting the true value of a_f as measured through the specimen thickness (particularly for long values of a_f). In addition, the results in Figure F-1

10 Ni Normal-Purity

$*K_{I_o} = 50.2$ $*K_{I_o} = 40.2$

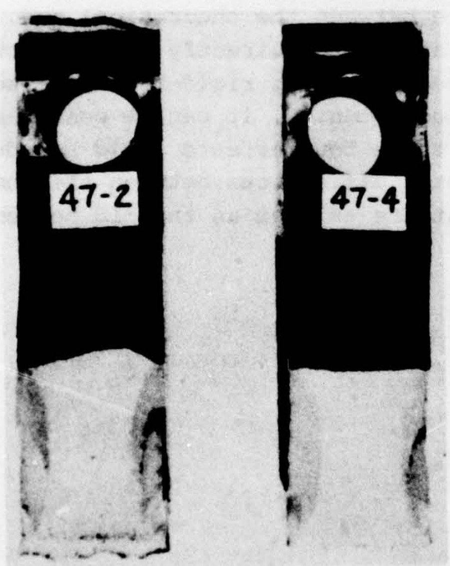
$*K_{I_f} = 36.1$ $*K_{I_f} = 27.4$



18 Ni Normal-Purity

$*K_{I_o} = 39.7$ $*K_{I_o} = 29.9$

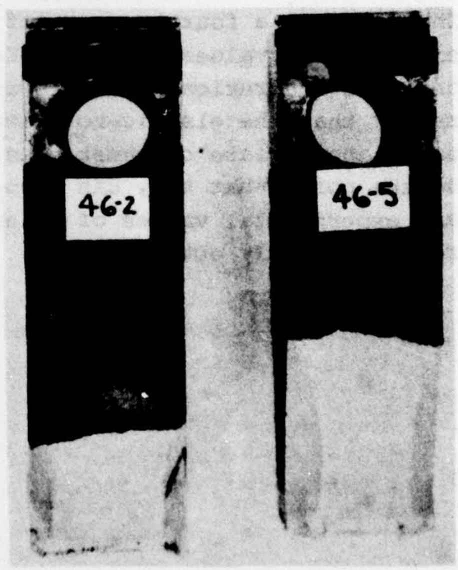
$*K_{I_f} = 24.1$ $*K_{I_f} = 25.7$



10 Ni High-Purity

$*K_{I_o} = 99.5$ $K_{I_o} = 87.3$

$*K_{I_f} =$ N/A $K_{I_f} = 53.7$



18 Ni High-Purity

$*K_{I_o} = 69.4$ $*K_{I_o} = 49.9$

$*K_{I_f} = 35.4$ $*K_{I_f} = 33.7$

* All K_{I_o} and K_{I_f} values are in terms of Ksi $\sqrt{\text{inch}}$.

Typical SCC Fracture Surfaces of 1T Modified WOL Specimens of Normal- and High-Purity 10Ni and 18Ni Steels at Test Termination at $t_f \doteq 7000$ hours in a 3.5 Percent NaCl Solution

18-4281A
18-4282A
18-4283A
18-4284A

show that some specimens exhibited through-thickness values of a_f that are less than the corresponding value of a_f from surface measurements. Such differences for these specimens with shorter and curved through-thickness crack fronts are consistent with the result that the theoretical values of P_f and K_{If} (calculated on the basis of surface a_f values) are somewhat lower than they should be and generally under estimate the experimentally measured results by values in the general estimated range of 5 to 10 percent or so.

The results in Tables F-1 and F-2 also are consistent in suggesting that some of the differences obtained between the theoretical and experimental values can be explained on the basis of long-term plasticity or creep at the crack tip that allows the two halves of the crack to displace laterally without extension, thereby leading to consequent load drop-off. This seems to be particularly supported by results from several specimens that exhibited little or essentially no crack extension (Δa_{SCC}) but still yielded experimental values of P_f and K_{If} that were of the order of 1 to 3 percent less than the corresponding values of P_o and K_{Io}.

A third possible effect could be the influence of wedging action of corrosion products, already mentioned briefly above. However, each of the three effects cited would appear to be of second- or third-order in nature. In addition, a fourth source of difference between the theoretical and experimental values of P_f and K_{If} can be attributed directly to the fact that the theoretical values were determined using the rigid-bolt analyses rather than the elastic-bolt analysis. Consequently, it can be seen that, under appropriate circumstances, each of these four effects could be additive to the point that they can account for total differences between the theoretical and experimental values of P_f and K_{If} that are as high as the ±18 percent range currently obtained.

APPENDIX G

CURRENT STATUS FOR DETERMINATIONS OF K_{Iscc}

The concept of an SCC threshold and associated designation, K_{Iscc}, has been the subject of much controversy in the past. In particular, the symbol K_{Iscc} has been used widely, loosely, and in an indiscriminant fashion without regard for either (1) validity of LEFM concepts, (2) a sound engineering basis of formulation, or (3) recognition of real material behavior. A decade ago, such a K_{Iscc} value was portrayed as a level below which absolutely no crack extension would occur. In recent years it has become increasingly clear that this is not necessarily the case and that such a K_{Iscc} value is often merely only representative of the line of demarcation between substantial and minimal crack extension. In the present view, substantial crack extension corresponds to generally rapid crack-growth rates and true SCC, whereas minimal crack extension corresponds to very slow crack-growth rates that are broadly related to the process of general corrosion at a crack tip. Furthermore, and more importantly, the earlier view of K_{Iscc} appears to be an idealization that is the exception rather than the rule for most material-environment combinations that lead to general corrosion behavior (e.g., present case). In contrast, the more recent and more general view of K_{Iscc} both recognizes and is completely consistent with the long-standing phenomena of general corrosion and localized (pitting or crevice) corrosion behaviors.

Despite the fact that most SCC tests with precracked specimens have been conducted with steels in various saline solutions (which will exhibit general corrosion), the earlier idealized view of K_{Iscc} was one that was largely developed on the basis of tests of this type that were of a short-term nature ($t_d \cong 100$ to 500 hours) and for which little or no measurable crack extension below K_{Iscc} was observed because of limited time availability. In contrast, the more recent view of K_{Iscc} has been developed on the basis of long-term tests ($t_d \cong 5000$ to 30,000 hours) on various steels which have given clear evidence of small but distinct values of crack extension (on the order of $\Delta a_{scc} = 10$ to 100 mils) for $K_{Io} < K_{Iscc}$. Moreover, such small values of Δa_{scc} appear to be primarily dependent on time and largely independent of K_{Io} level below K_{Iscc}. In addition, the occurrence of such small crack extensions for most steels tested in common aqueous or saline solutions (distilled water, 3.5% NaCl, synthetic sea water, natural sea water) is certainly quite understandable because the corresponding general corrosion-rate value (from smooth surfaces) for nearly all steels in such environments is on the order of 5 mils per year. The small crack extensions thus observed for such tests on steels would appear to clearly be the production of (1) a cumulative effect of time for a given basic general corrosion rate and/or (2) the high possibility of an intensified rate of general or crevice corrosion at the tip of a crack subjected to an applied static stress within a corrosive environment.

A further aspect concerned with existing confusion relative to K_{Iscc} is that such a value can be evaluated on the basis of Δa_{scc} occurring at the tip of a sharp fatigue precrack (initiation technique) and/or on the basis of an SCC crack propagating in a decreasing K_{Ii} field to ultimately arrest at the K_{Iscc} value (arrest technique). In particular, there has been considerable confusion over, first, whether a K_{Iscc} value exists, and, secondly, if it does exist, whether or not measurement with the initiation versus arrest techniques yield the same or widely different values. A major factor concerned with both of these questions has been the use of inadequate SCC test time (t_f)—particularly for those studies concerned with evaluation of the initiation versus arrest techniques for a single material-environment combination. A further aspect of such general confusion has been the fact that incubation periods do exist for SCC tests conducted with fatigue precracked specimens, and that such values are systematically dependent on K_{Io} and can be extensive in magnitude (t_{inc} = 1000 to 10,000 hours or more).

Recent studies[6,7] at this Laboratory have suggested that meaningful assessments of K_{Iscc} should be made for tests conducted with the crack-arrest technique (present case) using a crack-growth-rate value of $(\frac{da}{dt})_f \leq$ 1.0×10^{-5} inch/hour (2.5×10^{-5} cm/hour). In addition, it was determined that whereas a value of $(\frac{da}{dt})_f \leq 1.0 \times 10^{-6}$ inch/hour would be even more desirable as a discriminating rate value, the results of extensive tests on several high-strength steels (t_f = 12,000 hours) showed that such a value could <u>only be approached and not attained</u> with reliable measurements.

The SCC growth-rate value employed in the present study for assessment of K_{Iscc} is 1×10^{-5} inch/hour. From the standpoint of assessment with the initiation technique, it is helpful to note that such a rate value corresponds to a crack-extension rate of Δa_{scc} = 10 mils (0.010 inch) for a time increment of Δt = 1000 hours.

APPENDIX H

EXTENDED DISCUSSION OF STRUCTURAL SIGNIFICANCE OF SCC RESULTS FOR 10Ni STEELS

The substantial increase in both K_{Iscc} and associated a_{cr} value for the onset of SCC are not the only benefits of high purity level in 10Ni steel. While such benefits are unquestionably of first and foremost importance for long-term SCC applications under total immersion conditions, other benefits of high-purity level in 10Ni steel are also available for both the same and less severe applications. These include four items (described in greater detail below) as follows: (1) longer values of t_{inc} for $K_{Ii} > K_{Iscc}$, (2) slower values of $(\frac{da}{dt})$ for $K_{Ii} > K_{Iscc}$, (3) substantial increase in crack tolerance between the onset of SCC at a_{cr} corresponding to K_{Iscc} and the onset of complete catastrophic fracture at a_{cr} corresponding to K_{Ic}, and (4) the potential for moderate or substantial increases in the critical levels for SCC ($K_{Iscc} \rightarrow$ "K_{scc}") and fracture ($K_{Ic} \rightarrow K_c$) due to changes in state of stress from plane-strain to plane-stress (generalized or intrinsic) when structural plate thicknesses less than that required for valid LEFM results are employed.

Items (1) and (2) above are clearly related to structural applications that are less severe than long-term total immersion, such as either relatively short-term applications and/or others involving only occasional immersion in the SCC environment. The benefits of item (1) above are clearly evident in Table 9, as was discussed in general terms earlier. In terms specific to the present discussion, these results show that the incubation periods for normal-purity 10Ni steel from $K_{Io} \cong 1.5$ to $2.5\ K_{Iscc} = 40$ to $65\ ksi\sqrt{inch}$ range between $t_{inc} = 2$ to 10 hours, whereas the corresponding periods for the high-purity 10Ni steel from $K_{Io} \cong 1.5$ to $2.5\ K_{Iscc} = 70$ to $130\ ksi\sqrt{inch}$ range between $t_{inc} = 100$ to 1000 hours. That is, when the same ratios of K_{Io} levels above the corresponding K_{Iscc} are considered, the t_{inc} values for the high-purity 10Ni steel are about two orders of magnitude (factors of 100) larger than those for the normal-purity 10Ni steel. In regard to item (2) above, the results shown in Table 11 can be used to provide evidence, which is based on very crude calculations, to show for the same relative ranges of $K_{Io} \cong 1.5$ to $2.5\ K_{Iscc}$ considered for each steel that the average values of $(\frac{da}{dt})$ for the high-purity 10Ni steel are about 2 to 3 or more times slower than the corresponding values for the normal-purity 10Ni steel. Such evaluations are based on the extent of Δa_{SCC} exhibited at the $t_i = 4000$-hour mark in Table 11 using a value of time increment that otherwise neglects the corresponding t_{inc} values ($\Delta t = t_i$). More detailed comparisons show that such a factor is even larger when only the highest levels of the range are considered for each steel ($K_{Io} = 130\ ksi\sqrt{inch}$ for high-purity 10Ni steel and $K_{Io} = 65\ ksi\sqrt{inch}$ for the normal-purity 10Ni steel).

Items (3) and (4) above are equally applicable for both the most severe SCC conditions of long-term total immersion and the conditions of lesser severity already described above. In this connection, more detailed treatments of a_{cr} calculations and state of stress influence on SCC and fracture behaviors have been given elsewhere.[2,8)] However, in order to clarify in brief terms the specific benefits of purity in item (3) above, it must be recalled that the fracture-toughness levels have been determined to be $K_{Ic} = 73$ ksi$\sqrt{\text{inch}}$ for the normal-purity 10Ni steel and $K_{Ic} = 250 \pm 50$ ksi$\sqrt{\text{inch}}$ for the high-purity 10Ni steel. The benefits can be seen when these results are evaluated in terms of the corresponding a_{cr} value for fracture compared with the corresponding a_{cr} value for SCC. In particular, for a crack to grow from $K_{Iscc} \cong 23$ ksi$\sqrt{\text{inch}}$ to K_{Ic} for the normal-purity 10Ni steel, the value of a_{cr} must be 10.0 times larger, whereas for crack growth from $K_{Iscc} \cong 53$ ksi$\sqrt{\text{inch}}$ to $K_{Ic} = 250$ ksi$\sqrt{\text{inch}}$ for the high-purity 10Ni steel, the value of a_{cr} must be 22.2 times larger. These benefits of purity can be seen even more clearly when indexed relative to the previous example given above for a_{cr} relative to K_{Iscc}. That is, for the same given set of fixed conditions (σ_D and σ_{ys}) for static loading in a 3.5 percent NaCl solution, the value of critical crack length for the normal-purity 10Ni steel at the onset of SCC would be $a_{cr} = 0.160$ inch relative to that for final fracture at $a_{cr} = 1.60$ inch, and the corresponding values for the high-purity 10Ni steel at the onset of SCC would be $a_{cr} = 1.00$ inch relative to that for final fracture at $a_{cr} = 22.2$ inches. This much higher crack tolerance for the high-purity 10Ni steel can be seen to lead to distinct benefits in terms of "catching a crack" during routine nondestructive inspections of structural integrity, particularly when combined with the benefits of slower $(\frac{da}{dt})$ in item (2) above.

The benefits of purity relative to item (4) above relate to the possible usage of plate thicknesses that are less than that required for valid plane-strain conditions according to the accepted criterion of $B_{min} = 2.5 \left(\frac{K_{cr}}{\sigma_{ys}}\right)^2$, where $K_{cr} = K_{Ic}$ or K_{Iscc} and the applicability of the relationship for the latter SCC value is less than certain. For the currently measured values of K_{Iscc} and K_{Ic} and the appropriate value of yield strength (σ_{ys} = 216 ksi) in Table 6, it can be seen that such state-of-stress benefits would occur for structural plate thicknesses less than $B_{min} = 0.150$ inch (3.75 mm) for SCC at K_{Iscc} and $B_{min} = 3.35$ inches (8.5 cm) for fracture at K_{Ic} for the high-purity 10Ni steel. Although such benefits are likely to be small or nonexistent in elevating a_{cr} for the onset of SCC in most structural applications, the likelihood is reasonably high that some benefits in elevation of a_{cr} for final fracture would occur due to a change in the state of stress from plane-strain to transitional or plane-stress when structural plate thicknesses of 1 inch or less are employed, particularly in view of the associated high-energy shear lips developed on the corresponding fracture surfaces, Figures 1 and 2.

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